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Battelle Memorial Institute

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April 14, 1959

Mr. Frank E. Resnik
Instrument and Physics
Research and Development
Philip Morris, Incorporated
P. O. Box 3D
Richmond 6, Virginia

Dear Frank:

This is our Nineteenth Monthly Progress Report on "An Investigation of the Dynamic Behavior of Cigarette Smoke" covering the month of March, 1959. Studies were made of (a) the particle-size distribution of diluted smoke from Marlboro cigarettes with and without the filter in place, and (b) the possible increase in filtering efficiency that may result from providing residence time for coagulation of smoke particles before they are filtered. Also, the lung retention studies were initiated, and detailed plans were laid for future work.

Effect of Filter on Particle-Size Distribution of Diluted Smoke

To gain a better understanding of the mechanism of filtration, the smoke from Marlboro cigarettes, with and without the filter in place, was sampled in the cascade impactor after dilution with 300 volumes of air. The over-all length of the cigarettes, both with and without the filter, was maintained constant so that the length of travel of the smoke would be uniform. This investigation was suggested by previous studies which have shown that prompt dilution of the smoke markedly reduces coagulation and thereby reduces the mass median diameter of the smoke particles.

Figure 1 is a log-probability plot of the particle-size distributions for the diluted smoke from cigarettes with and without filters. The filter causes little difference in the particle-size distribution of the diluted smoke except for a slight decrease in the percentage. of larger particles.

Because both cigarettes had the same total length and were smoked to a 25-mm-butt length, the difference in the total number of smoke particles leaving the cigarette was a measure of the difference

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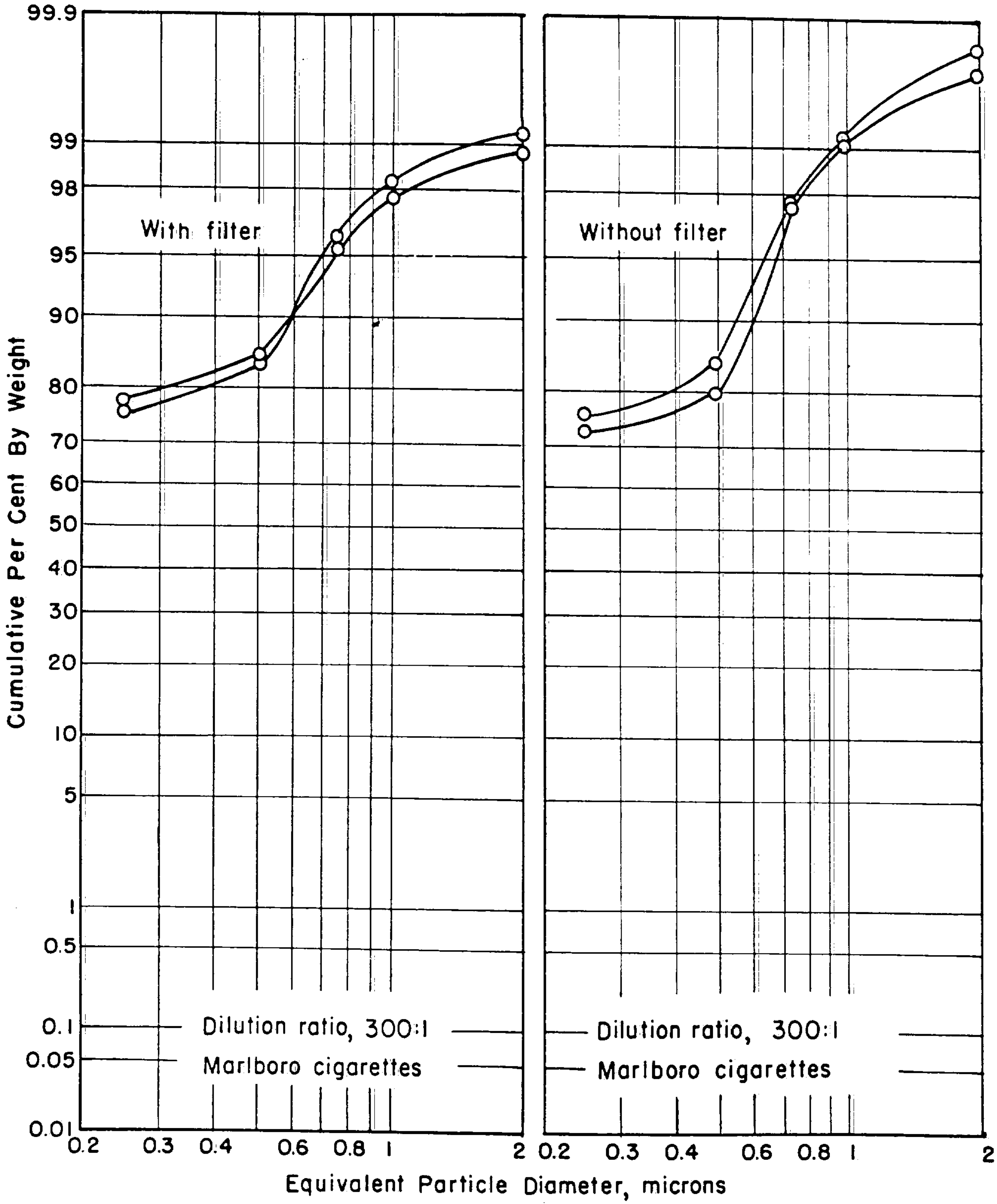

FIGURE I. PARTICLE-SIZE DISTRIBUTION OF DILUTED CIGARETTE SMOKE WITH AND WITHOUT FILTER

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in the filtering efficiency of the filter as compared to an equivalent length of tobacco. The smoke was diluted with 300 volumes of room air promptly after formation, thus, coagulation was greatly reduced and particle-size distribution did not change appreciably after the smoke left the end of the cigarette. Consequently, as shown in Figure 1, the size distributions of filtered and unfiltered smokes were nearly the same.

Possible Increase in Filtering Efficiency by Providing Residence Time For Coagulation of Smoke Particles

Earlier studies showed that coagulation, during the first few seconds after the smoke is formed, greatly increases the sizes of the smoke particles. Therefore, trials were made to determine the effect of introducing a void space between the cigarette butt and the filter to allow the smoke particles to coagulate before they reach the filter. The coagulated particles would be larger in size and a greater portion would be removed by the filter.

Figure 2 is a log-probability plot of the particle-size distributions obtained for unmodified filter-type cigarettes and for others which had a 10-inch void space, consisting of a 8-mm glass tube, between the filter and the cigarette butt. This space provided a residence time of about 0.7 second between the tobacco and the filter.

This figure indicates that no significant difference in the particle-size distribution resulted when a void space was provided between the cigarette and the filter. A possible explanation is that the cigarette smoke is diluted appreciably by mixing with the air contained in the void space and coagulation is thereby retarded. Turbulent mixing of smoke with air was observed as the smoke passed through the glass tube. This turbulent mixing probably could be reduced if the void space was packed with a honeycomb-like material to promote laminar flow. These trials will be repeated if a suitable streamlining material can be obtained.

Lung Retention Studies

The literature survey on lung retention has been completed and is in the process of being reproduced as the Third Phase Report.

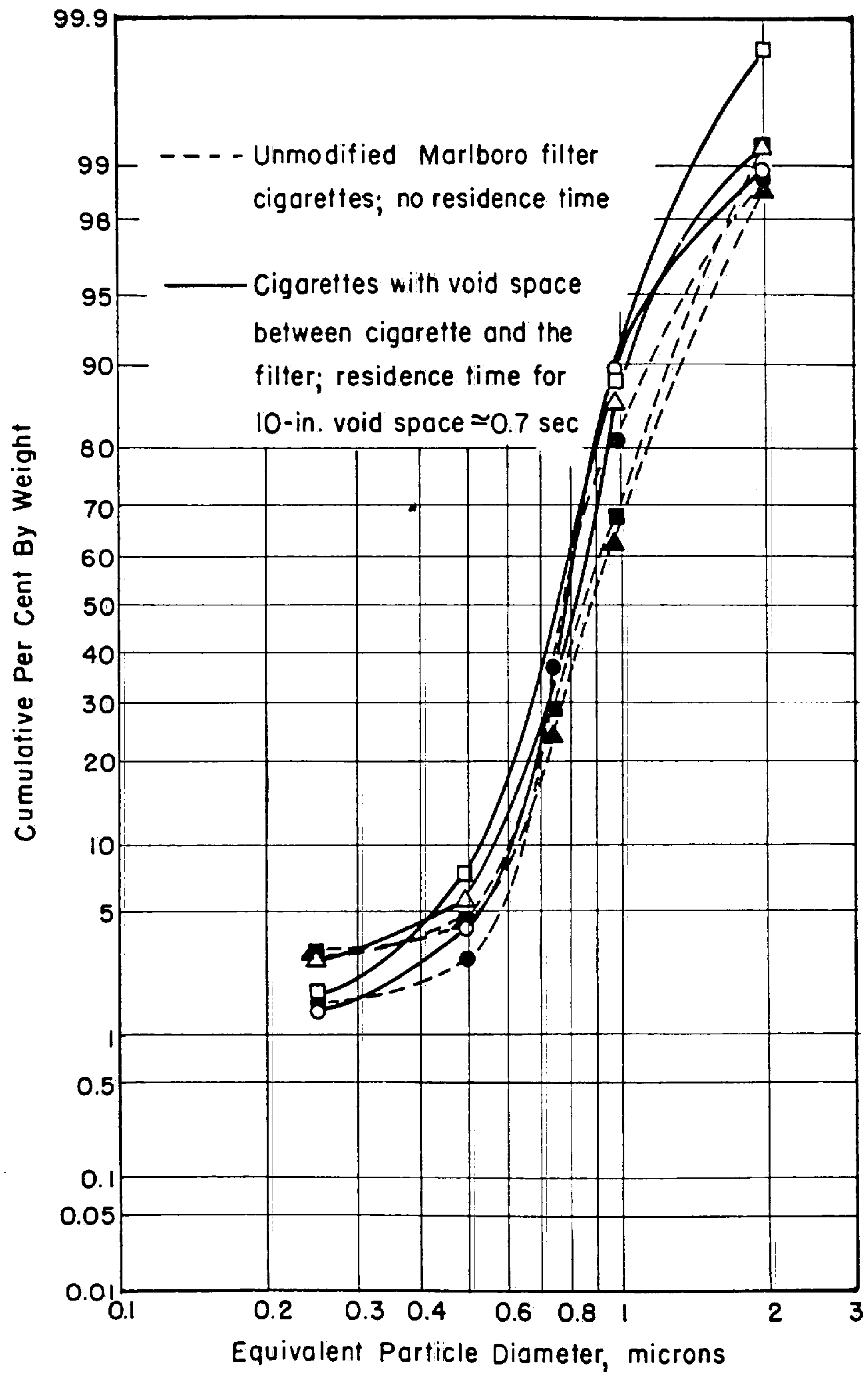

FIGURE 2. EFFECT OF RESIDENCE TIME ON THE EFFICIENCY OF A CIGARETTE FILTER

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The Statham Model PM-197 pressure transducer, which will be used with a sensing element to measure smoke flow rates for the lung-retention studies, has been received. The device requires a 5-volt d-c power input and produces a 20 millivolt output at a maximum pressure differential of 0.01 psi.

Figure 3 is a schematic drawing of the flow-metering device. Preliminary trials have been made with a crude sensing element to determine if this transducer is compatible with amplifiers and recorders available at Battelle to form a pneumotachometer. Results thus far are encouraging.

During April a suitable sensing element will be designed which will produce the required pressure drop for the low flow rates encountered. An effort will be made to maintain a low volume within the pneumotachometer and to reduce deposition of smoke particles by minimizing the restriction in the sensing element.

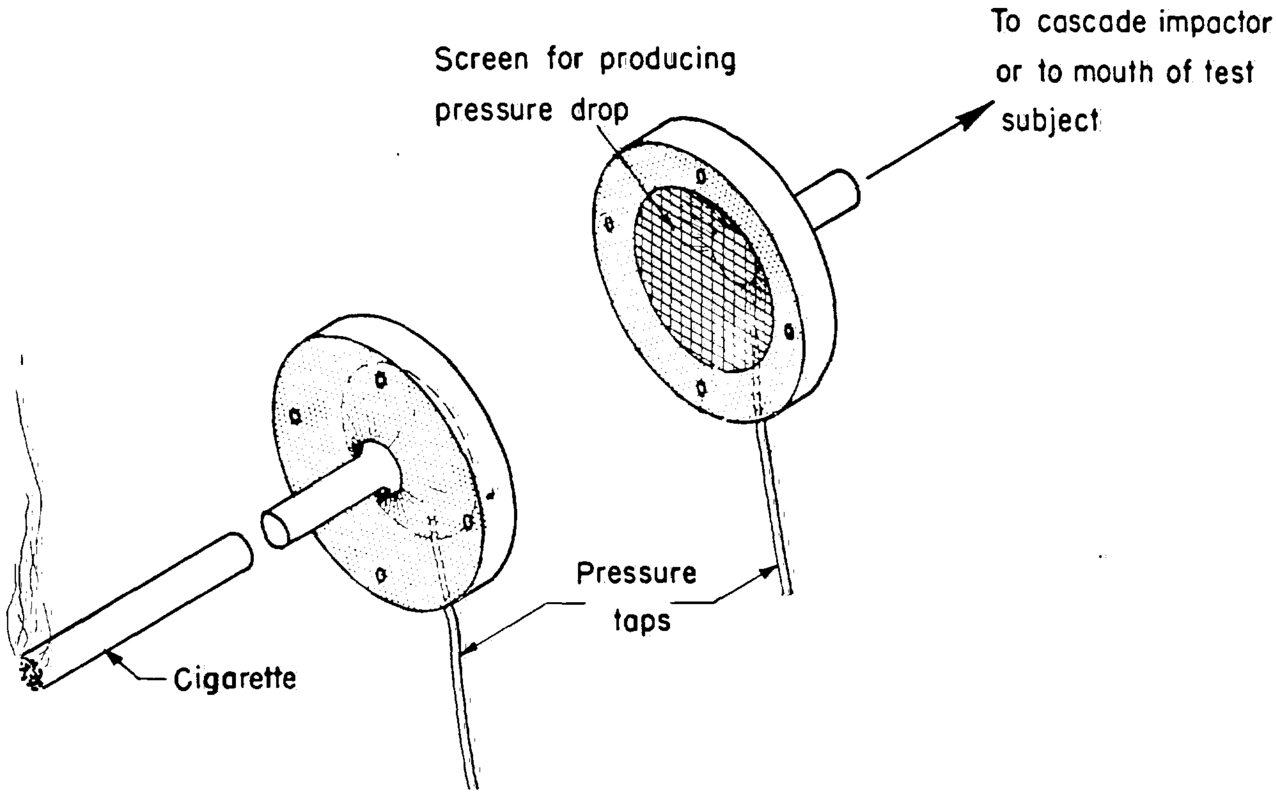
During April, the pneumotachometer will be calibrated and the volume of normal cigarette puffs from several individuals will be measured.

Future Plans

The tentative experimental procedure to be followed during the investigation of lung retention of cigarette smoke is outlined in the minutes covering the meeting held with the representatives of Philip Morris at Battelle on March 25, 1959. In addition to calibrating the pneumotachometer, it will be necessary to determine the number of exhalations required to purge the lungs of smoke particles. Also, a technique will be developed for obtaining a smoke sample for analysis in the cascade impactor. The burning rate of the cigarette and the volume of the smoke for the sample to be analyzed will be controlled as closely as possible to duplicate the sample of smoke inhaled by the test subject.

Appendix A is a sample of the questionnaire to be filled in by those who serve as test subjects for the lung retention study.

Appendix B is a derivation of the mathematical expression for the theoretical decrease in the concentration of cigarette smoke in the lungs resulting from successive inhalations of tidal volumes of room air.



Exploded View of Sensing Element

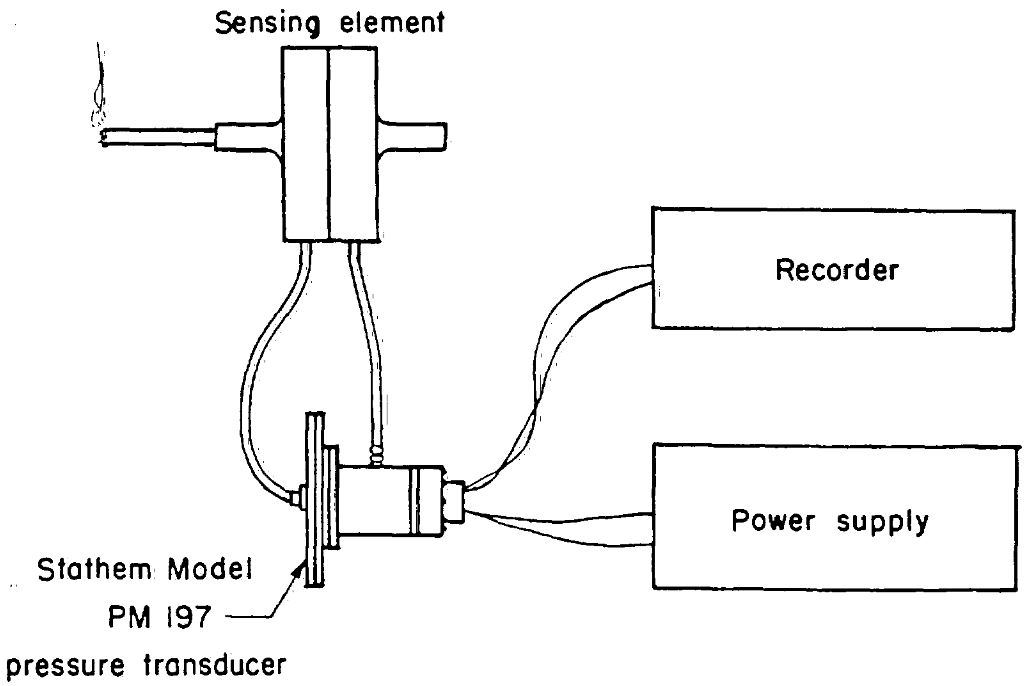


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FIGURE 3. SCHEMATIC DRAWING OF CIGARETTE SMOKE FLOW-METERING DEVICE

We shall appreciate any comments you may have concerning this report and concerning plans for the lung retention studies as outlined in the minutes of our meeting at Battelle on March 25.

Sincerely yours,

Ralph I. Mitchell

Ralph I. Mitchell

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Enc. (10)

APPENDIX A

QUESTIONNAIRE
TOBACCO SMOKE RETENTION PROJECT

Name________________________________ Race________ Marital Status (S M W D)

Address____ Sex______________

Age______ Occupation________________________________ Date______________

Height (in.)__________ Weight____________

1. Do you smoke? Yes____ No____

2. Have you ever smoked? Yes____ No____

If yes, what type, quantity and duration of smoking?__________________

____

____

3. Do you now have a respiratory illness? (Cold, bronchitis, flu, virus, etc.) Yes____ No____

4. Have you recently had a respiratory illness? Yes____ No____

5. Do you have any of the following diseases or symptoms?

	Yes	No		Yes	No
Influenza	___	___	Heart Disease	___	___
Pneumonia	___	___	Cough	___	___
Sinusitis	___	___	Expectoration	___	___
Asthma	___	___	Wheezing	___	___
Turberculosis	___	___	Shortness of Breath	___	___
Other Respiratory Disease	___________		Chest Pain	___	___

____

Explain yes answers:

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APPENDIX B

Theoretical Decrease in the Concentration of Cigarette Smoke in the Lungs Resulting from Successive Inhalations of Tidal Volumes of Room Air

A simplified mathematical derivation of the decrease in the concentration of cigarette smoke in the lungs may be obtained under the following assumptions. Suppose that there exists in the lungs an initial concentration of cigarette smoke particles which are uniformly distributed throughout the air volume contained in the lungs. Suppose further that this state is followed by alternate exhalations of smoke and inhalations of clean air. Because with each exhalation smoke particles are removed from the lungs and smoke particles are not added in the subsequent inhalation, it is clear that the concentration of smoke in the lungs will be progressively decreased. For mathematical simplicity it is assumed that the inhaled air is mixed instantaneously and uniformly with the residual air in the lungs, and that the concentration of smoke does not decrease because of deposition in the lungs.

Under these assumptions, let C_o denote the initial concentration of particles/cm^3 in the lungs initially, and let C_K denote the concentration after K inhalations of a tidal volume ν of clean air which is mixed with a functional residual volume V. As shown later the concentration ratio C_K/C_o is then given by the equation:

$$\frac{C_K}{C_o} = \left[\frac{1}{1+f}\right]^K \quad , K = 0, 1, 2, \ldots ,$$

where $f = \frac{\nu}{V}$.

Figure 4 shows a plot of this equation for a sequence of 10 inhalations for various values of f, the ratio of tidal volume to functional residual volume. The plot shows, for example, that for K = 4 and f = 1/4, the concentration ratio is approximately 0.40. This means that the concentration ratio is decreased to approximately 40 per cent of the initial concentration after 4 inhalations when the tidal volume is 1/4 of the functional residual volume; after 10 inhalations the concentration is reduced to approximately 10 per cent of the initial concentration. Similar results may be obtained from the figure for other values of K and f.

Derivation of the Theoretical Equation. The equation for the concentration ratio may be derived as follows. The number of smoke particles in the lungs just prior to the K^{th} inhalation is given by VC_K. With the addition of a tidal volume ν the ratio of the number of smoke particles to the total volume is given by $VC_K/(V+\nu)$ which is equal to C_{K+1}. Thus,

$$C_{K+1} = \left[\frac{V}{V+\nu}\right] C_K$$

Assumptions:

1. At $t = 0$ a concentration of cigarette smoke exists in the lungs equal to C_0 particles/cm^3
2. Subsequent inhalations consist of room air
3. Smoke is uniformly distributed in the lungs
4. Concentration is not decreased by particle deposition in the lungs
5. Curves based on theoretical results

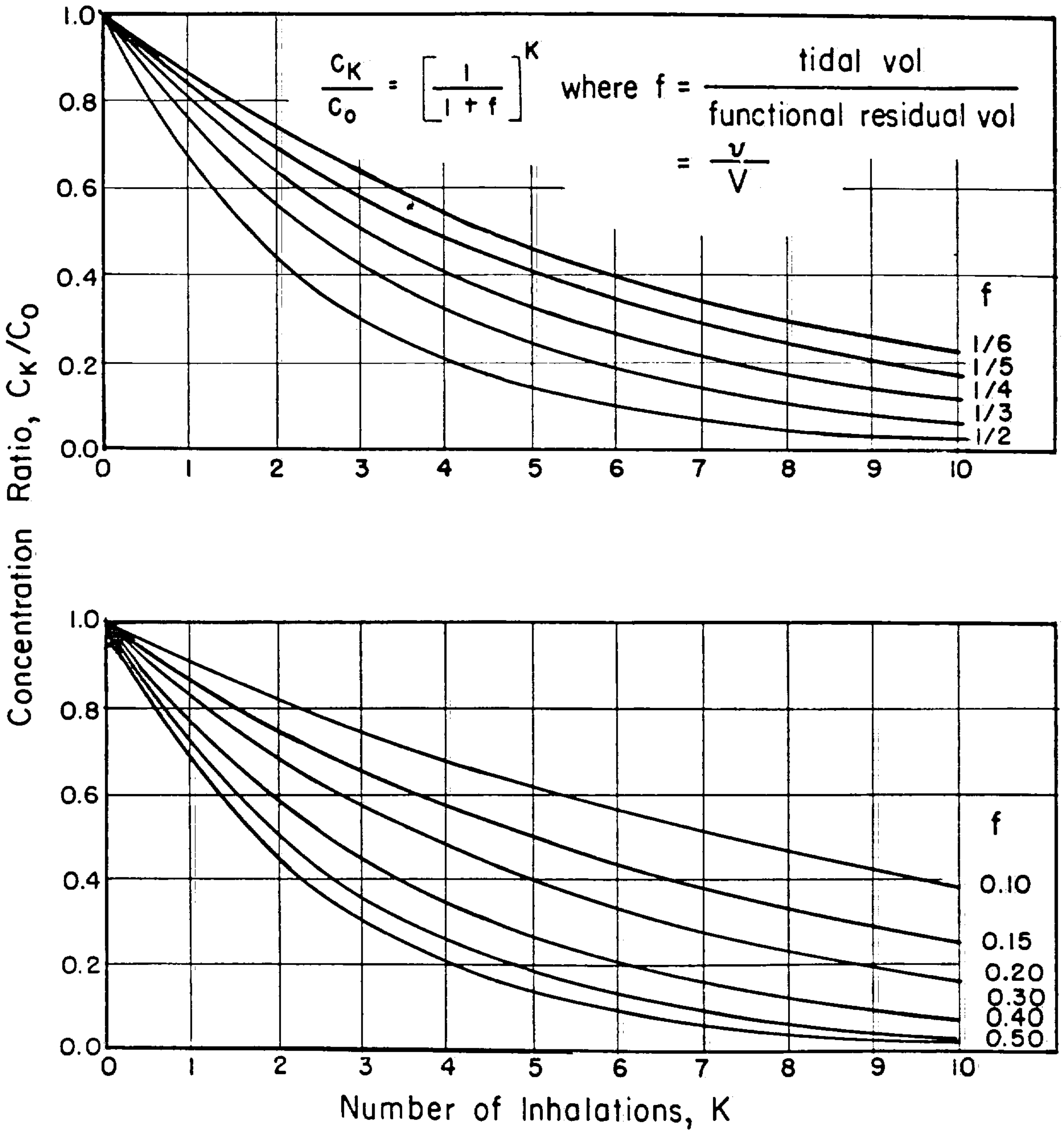

FIGURE 4. THEORETICAL DECREASE IN CONCENTRATION OF CIGARETTE SMOKE IN THE LUNGS AS A FUNCTION OF NUMBER OF INHALATIONS FOR VARIOUS RATIOS OF TIDAL VOLUME TO FUNCTIONAL RESIDUAL VOLUME

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and this result may be written as a linear homogeneous difference equation:

$$C_{K+1} - \left[\frac{1}{1+f}\right] C_K = 0$$

where $f = \nu/V$.

The solution to this equation is easily found to be

$$C_K = \left[\frac{1}{1+f}\right]^K C_o$$

so that the concentration ratio is given by

$$\frac{C_K}{C_o} = \left[\frac{1}{1+f}\right]^K .$$

Generalization of Preceding Result

The preceding result is based on the assumption that the tidal volume ν and functional residual volume V are constant. More generally, suppose that these volumes vary in a sequence of breaths where each breath is composed of one inhalation followed by one exhalation. Then let ν_K and V_K denote the inhaled volume and residual volume associated with the K_{th} breath. The number of smoke particles in the lungs at the end of the K^{th} breath is given by $V_K C_K$ where C_K denotes the concentration of smoke in particles/cm^3. During the $(K+1)^{st}$ breath a volume ν_{K+1} is added to V_K so that the concentration of smoke in the lungs at the end of the $(K+1)^{st}$ breath is given by

$$C_{K+1} = \frac{V_K C_K}{V_K + \nu_{K+1}} , \quad K = 0, 1, \ldots$$

This result may be written as

$$C_{K+1} = \left[\frac{1}{1+\dfrac{\nu_{K+1}}{V_K}}\right] C_K, \quad K = 0, 1, \ldots$$

The solution of this equation for C_K is easily found to be

$$\left(\frac{C_K}{C_o}\right) = \left[\prod_{i=1}^{K} \left(\frac{1}{1+\dfrac{\nu_K}{V_{K-1}}}\right)\right], \quad K = 0, 1, \ldots$$

This generalized result gives the concentration of smoke for any sequence of inhaled volumes of air.

Special Case I. If the residual volumes V_K are all equal to a constant value V, then the concentration ratio at the end of the K^{th} breath is given by

$$\left(\frac{C_K}{C_o}\right) = \prod_{i=1}^{K} \frac{1}{1+\frac{\nu_K}{V}} \quad , K = 0, 1, \ldots$$

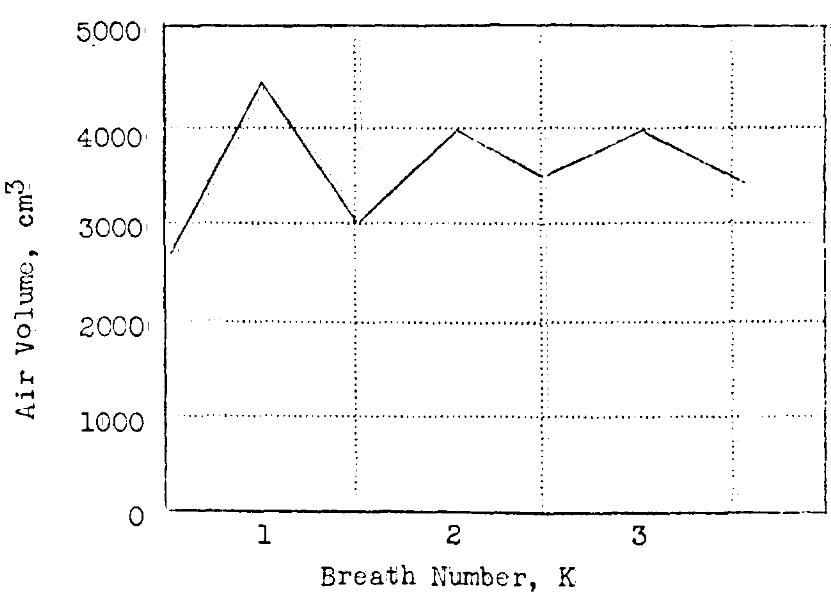
Special Case II. If the inhaled and exhaled volumes are equal to ν for every breath, then $V_K = V$ and $\nu_K = \nu$ for all K and the concentration ratio becomes

$$\left(\frac{C_K}{C_o}\right) = \left(\frac{1}{1+\frac{\nu}{V}}\right)^K \quad , K = 0, 1, \ldots$$

which agrees with the case derived earlier.

Example of General Case

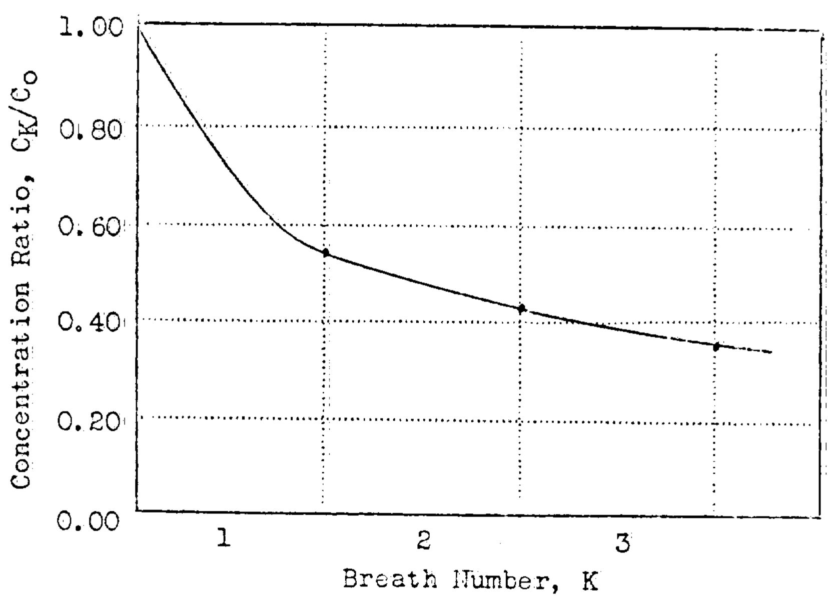
Suppose the following plot gives the sequence of inhalations and exhalations for three breaths.



The computations of the concentration ratio are given in the table below:

Breath No.	Inhaled Volume, cm^3	Residual Volume, cm^3				
K	ν_K	V_K	ν_K/V_{K-1}	$1+(\nu_K/V_{K-1})$	$[1+(\nu_K/V_K-1)]^{-1}$	C_K/C_o
0	-	2500	-	-	-	-
1	2000	3000	0.800	1.800	0.556	0.556
2	1000	3500	0.330	1.330	0.752	0.417
3	500	3500	0.143	1.143	0.874	0.365

The concentration ratio C_K/C_o is shown as a function of breath in the following sketch:



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